Mechanics of Human Accommodation and Presbyopia

Weeber, H.A.

2008

8

General Discussion and Conclusion

8.1 Summary

The aim of this study was to determine the role of the mechanical properties of the lens matrix in the accommodative process, and especially how they influence the deformation of the crystalline lens during accommodation.

In a first exploratory analysis, a mechanical model was developed describing the mechanism of accommodation, based on existing literature data. The model consisted of three components: the lens matrix, the lens capsule and a schematic representation of the zonular fibers. For the young eye, this model predicted an acceptable amount of accommodation, which was reasonably close to what is measured clinically. For the older eye the predicted accommodative amplitude was considerably larger than clinical values, showing little signs of presbyopia. This deviation from the clinical situation could have a number of causes, the most important ones being (1) the stiffness values of the lens from the literature are not reflecting the true mechanical properties of the crystalline lens, (2) presbyopia is not caused by the increasing stiffness of the lens and (3) the modeling methodology is not adequately simulating the actual situation. The first two points are explicit subjects in this study. The last point has been briefly touched upon in chapters 6 and 7, and will also be discussed further on.

The exploratory analysis showed that when a model uses different stiffness values for the nucleus and the cortex, this can have a relative large effect on the accommodative amplitude in the simulation.

In a further explorative analysis, variations in the model have been investigated. The variations consisted of the introduction of Wieger's ligament, an age-dependent stiffness of the lens capsule and a pre-stressed lens capsule and lens matrix at the start of the simulation. Introducing Wieger's ligament in the model changed the relative contribution of the anterior and posterior lens surface to the total power change of the lens. With Wieger's ligament in the model, the anterior lens surface contributed more to the total change in lens power, bringing the simulation results closer to clinical observations. An increase of the stiffness of the capsule resulted in an increase in required zonular force, but did not lead to significant changes in accommodative amplitude. A pre-stress in the crystalline lens hardly influenced the accommodative amplitude or the required zonular force.

In a next phase of this study the mechanical properties of crystalline lenses of varying ages were determined using a dynamic mechanical analysis (DMA). DMA was performed on 39 human lenses, ranging in age from 18 to 90 years. The lenses were stored at -70 °C before being measured. The influence of freezing on the mechanical properties was determined using pairs of porcine lenses, with one lens measured directly after enucleation and the other after being stored frozen. The influence of freezing, as well as the measurement reproducibility and repeatability were small compared to the large differences with age that were found. The lenses exhibited a distinct viscoelastic behavior. The storage and loss compliance depended strongly on age and decreased a factor 1000 over a lifetime. The stiffness of the lens material increased exponentially with age.

In a further study, using fewer lenses, the mechanical properties of the lens were measured locally within the lens. In order to do so, the lens was cut in half along the equatorial plane. The stiffness was measured using an oscillating indenter, penetrating the lens at different locations in the cutting plane. The resistance to oscillation was measured at different frequencies. A full frequency sweep was however not possible, due to the expected influence of sample inertia on the measurement. Nevertheless, the results demonstrated that the dynamic shear modulus varied strongly with measurement location for all tested lenses. The stiffness gradient depends on the age of the lens. The results of the 10 measured lenses (age range: 19 to 78 years) indicate that the stiffness at both the center and the periphery increase with age, but at a different rate. At young age, the nucleus is softer than the cortex, and at older age, the nucleus is stiffer than the cortex.

The measured mechanical properties of human lenses were subsequently implemented in a finite elements model of accommodation. Compared to the exploratory model, 3 aspects were different in the new model:

(1) The surface curvatures of the lens were now derived from in vivo measurement data from Dubbelman et al.[1] of lenses in the maximum accommodated eye. From these data, a regression was

made to arrive at an average shape and thickness of the 40-year-old lens. The lens surfaces were aspherical.

(2) The loading parameters were adjusted. While in the explorative studies, the lens equator was stretched by 7% for all ages, now the lens was stretched with an equal force for all ages. The force was derived from the force required to stretch the 40-year-old lens by 7%.

(3) The new lens stiffness values were implemented, both the results of the measurements on entire lenses as well as the results of the local stiffness measurements. For the implementation of the local stiffness, the interior of the lens was modeled in concentric regions, each region having a uniform stiffness.

Thus, three variations of the model were defined, depending of the stiffness profile in the lens: (1) incorporating the classic uniform stiffness values measured by Fisher[2], (2) incorporating a uniform stiffness as measured by dynamic mechanical analysis on entire lenses and (3) incorporating the stiffness gradient obtained from local stiffness measurements. For the 40-year-old lens, all models predicted acceptable amounts of accommodation, reasonably close to clinical values. Model (1) demonstrated a very small decline in accommodative amplitude, similar to that shown in the original explorative analysis. Model (2), incorporating a uniform stiffness that increases exponentially with age, also showed just a small and almost linear decline of accommodative amplitude with age. Model (3) however showed an accelerated decline of accommodative amplitude after the age of 40 years approaching zero at the age of 60 years. These results demonstrate that the change in stiffness gradient is far more important than the magnitude of the stiffness itself. The accelerated decline in accommodative amplitude starts at the moment in life when the nucleus becomes stiffer than the cortex.

In model (3), with the stiffness gradient incorporated, the deformations within the lens were further analyzed. It was demonstrated that the thickness change during accommodation takes place mainly in the nucleus of the lens. This behavior is very similar to that found clinically, as measured by Dubbelman and co-workers[3] using Scheimpflug images.

The current study provides evidence that the gradient stiffness of the lens material can fully account for the loss off accommodation with age. The model predicts presbyopia about 10 years later than found clinically. This discrepancy could be due to shortcomings in the model and in the input data. The stiffness gradient was determined using only 10 human donor lenses, which also had been frozen prior to testing. On the other hand, the discrepancy could also indicate that more factors than were modeled in this study play a role in the development of presbyopia. Factors, like geometric changes with age, could be incorporated in a future mechanical model.

8.2 Modeling Methodology

In this study the mechanism of accommodation was described as a system consisting of the lens matrix, the lens capsule and the zonular fibers. The tip of the zonular fibers was connected to an actuator, which imposed a prescribed force or displacement onto the zonule. The exploratory analyses demonstrated that presbyopia could not be explained in a model using the lens stiffness data from literature.

As mentioned in chapters 6 and 7, the FE modeling methodology was validated by comparing the results of the model with in vivo measurements of an individual human subject[4], and by comparing the results of the model with lens-stretching experiments[5]. These validation studies were presented at conferences and will be summarized here.

The results of the model were compared with lens stretching measurement on human lenses, as described in chapter 6. A further verification of the FE model has been performed, comparing simulation results with lens stretching experiments for which the stiffness of the lens matrix was known[5]. These experiments concerned stretching experiments with lenses that were refilled with a silicone polymer[6]. For the comparison with simulation results, 8 human donor lenses were refilled with one of two silicone materials with different material stiffness. Subsequently, the lenses were stretched in a water bath and the change in lens diameter and in optical power were measured. The lens power change at 7% increase of the lens diameter was compared with simulation results (Figure 1). In the simulation, the same refractive indices of water and silicone were used as in the experimental situation: 1.428 for silicone and 1.333 for water. All other parameters of the model were as described in chapters 6, based on an average 40-year-old lens with uniform lens stiffness. The stretching experiments as well as the simulations demonstrated that the stiffness of the refill material had an effect on the achieved change in lens power, but that this effect was small when considering that the stiffness between the two silicone material differed by more than a factor of 4 (Figure 1).

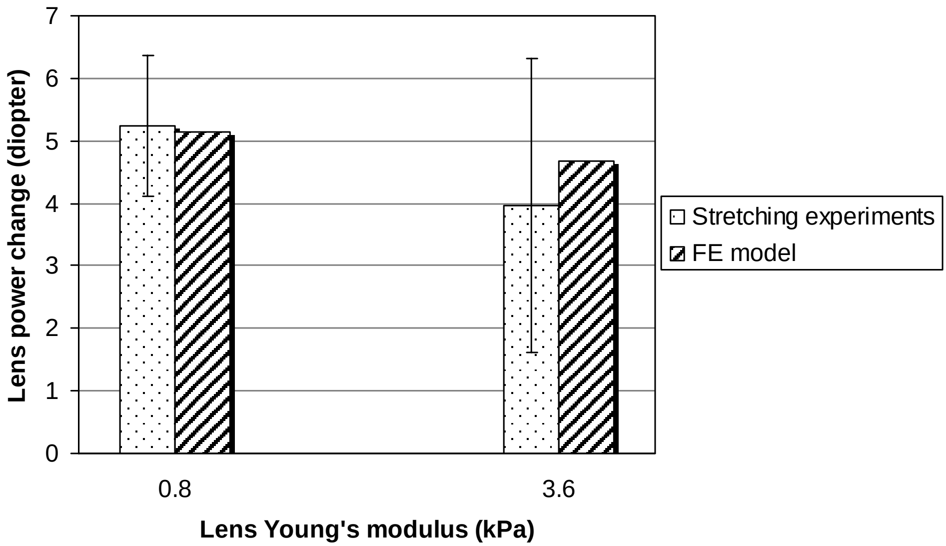

Figure 1. *Lens power change during stretching. Comparison of experimental and simulation results.*

In a further experimental verification of the modeling methodology, a custom FE model was built describing the shape of the lens of a particular 25-year-old subject, for which the radii and central thickness of the lens were measured using Scheimpflug images. The measurements were part of a study by Dubbelman and co-authors[1]. The shape of the lens was measured at several states of accommodative demand, up to the subject’s accommodative amplitude. In addition, the intraocular axial distances were measured, and the equivalent refractive index of the crystalline lens was determined using the measured geometry of the eye and the standard refractive indices for cornea, aqueous and vitreous[7]. For the lens of this subject, an equivalent refractive index of 1.436 was found and this value varied only little with accommodative demand. The shape of the stress-free lens in the FE model was created according to the measured shape of the maximum accommodated lens of the subject. Other parameters in the model were as described in chapters 6 and 7. The lens stiffness in the FE model was uniform, with a Young's modulus of 1.5 kPa, about the value of a 25-year-old lens. The lens diameter was then stretched by 7% and the change in lens power was determined using refractive indices 1.436 and 1.336 for the lens and aqueous respectively. This was compared to the lens power change, as determined by the Scheimpflug images. The results showed that the model predicted the maximum change of the lens very well (Figure 2). This confirmed that with a 7% stretch of the lens diameter the FE model can simulate the in vivo accommodative amplitude.

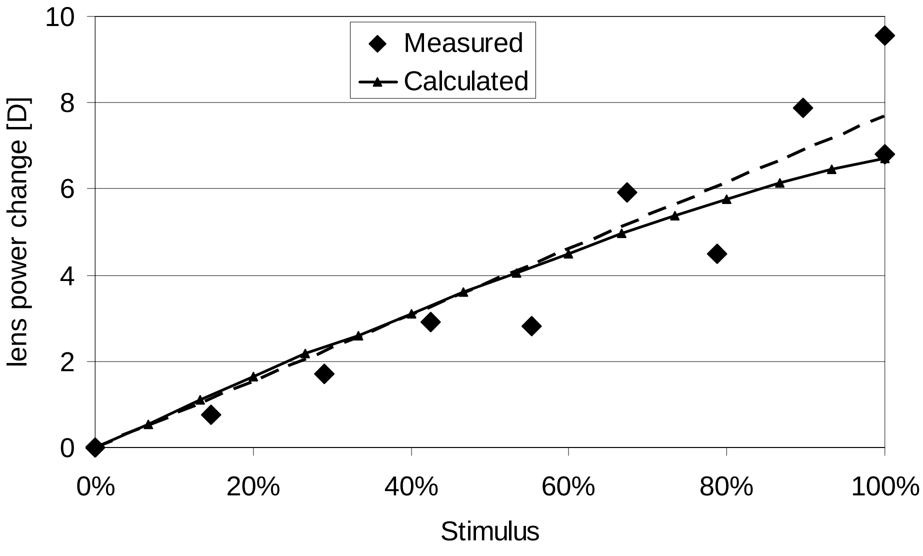

Figure 2. *Change in lens power as measured using Scheimpflug images and simulated in the FE model. During the measurements, the stimulus consisted of an accommodative demand up to the maximum attainable accommodation for this subject. For the FE calculations, the stimulus consisted of a stretch of the lens diameter up to 7%. Presented at ARVO 2003*[4].

The accommodative amplitude found in the FE model based on the individual subject is almost the same as for the general FE model, as described in chapters 6 and 7. Figure 3 shows the shape of the subject's lens together with the lens shape as used in chapters 6 and 7. These results indicate that individual differences in lens shape have a limited effect on the simulation results.

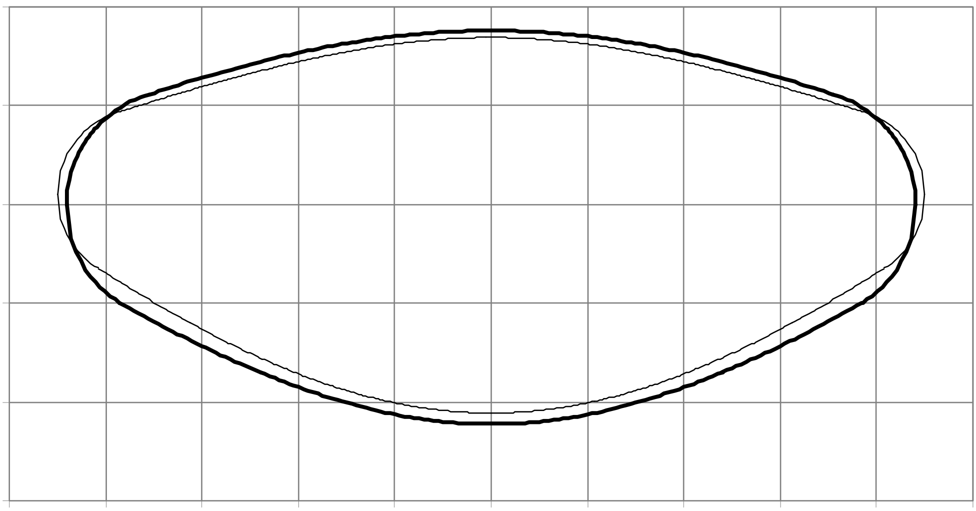

Figure 3. *Lens shape of the subject (thin line), together with the lens shape as used in chapters 6 and 7 (thick line). Both shapes are in the maximum accommodated state. The gridlines have a 1-mm separation.*

8.3 Presbyopia and Lens Refilling

During life, we gradually loose the ability to accommodate and by the age of 45-50 years, near vision becomes impaired (presbyopia). The medical need of presbyopic patients could be described as: to have good vision at a range of distances. Therefore, possible cures for presbyopia are not limited to restoration of accommodation. They could consist of any measure that restores good vision at a range of distances. The classical way to overcome presbyopia is by the use of reading glasses. Current surgical methods include the implantation of multifocal intraocular lenses and monovision with monofocal intraocular lenses. Also, reshaping the cornea (e.g. LASIK) can introduce an increase in depth of focus, resulting in acceptable vision at a range of distances[8,9]. Furthermore, intraocular lens designs are introduced which claim to accommodate[10]. The function of these lenses is based on a movement of the optic of the lens, induced by the action of the ciliary muscle and/or the pressure of the vitreous body against the lens surface. A theoretically ideal way to obtain good vision at a range of distances would be to restore accommodation in a way as close as possible to natural accommodation. Three of these methods are described in the literature: (1) Refilling the capsular bag with a flexible material[6,11-18], (2) Lens regeneration[19-21] or transplantation[22] and (3) softening the crystalline lens in vivo, by a laser treatment[23-25]. These methods rely on the idea that the cause of presbyopia lies within the lens, and that replacing the hard lens with a softer lens (artificial, regenerated or laser treated) will restore the ability to accommodate. While this is a well accepted assumption, there is still much debate in the scientific literature about the possible causes of presbyopia[26-41].

The results of this study can be applied in the research towards an accommodating intraocular lens, and specifically that of an artificial crystalline lens (ACL). The measured mechanical properties of the human lenses can serve as baseline data for the development of materials for ACLs. In addition, the modeling techniques employed in this study can be used to investigate the feasibility of lens refilling. Some studies have already been carried out[5,6,42-44].

The following describes an example of a simulation of lens refilling[42]. It is assumed that refilling takes place while the eye is under pressure, so that the lens is under zonular tension. The simulation consisted of the following steps (Figure 4): (1) as in chapters 6 and 7, the natural crystalline lens is stress-free and in the accommodated state; (2) The natural crystalline lens disaccommodates by introducing the zonular force, until the lens increases its diameter by 7%; (3) Assuming that the refilling volume is exactly the same as the original lens volume, and ignoring a small capsulorhexis needed for lens removal and refilling, refilling is modeled as a relaxation of the internal shear stresses of the lens matrix, combined with a change in mechanical properties of the lens matrix from that of the natural lens to that of the ACL material. During this process, the displacement on the distal end of the zonule is kept constant. In this simulation step the lens exhibits a small change in shape; (4) disaccommodation is modeled by releasing the zonular fibers.

The FE model was again based on the 40-year-old lens, lens capsule and zonular fibers, and with a gradient stiffness in the lens matrix of the 40-year-old eye. The refilling material was uniform and isotropic incompressible and had a Young's modulus of 0.5 kPa. In the second step of the simulation, the natural accommodative amplitude was 4.6 diopters (same as found in chapter 6). During the refilling process the shape of the lens changed. In order to maintain the same refraction after refilling, the refractive index of the refill material needed to be 1.428 (1.422 for the natural lens). After release of the zonular fibers, the lens power changed by 4.8 diopters, which is equivalent to an accommodation of 3.6 diopters. This demonstrated that for this case, accommodation can be maintained after a refilling procedure, but that the accommodative amplitude may be reduced, in this case by about 20%.

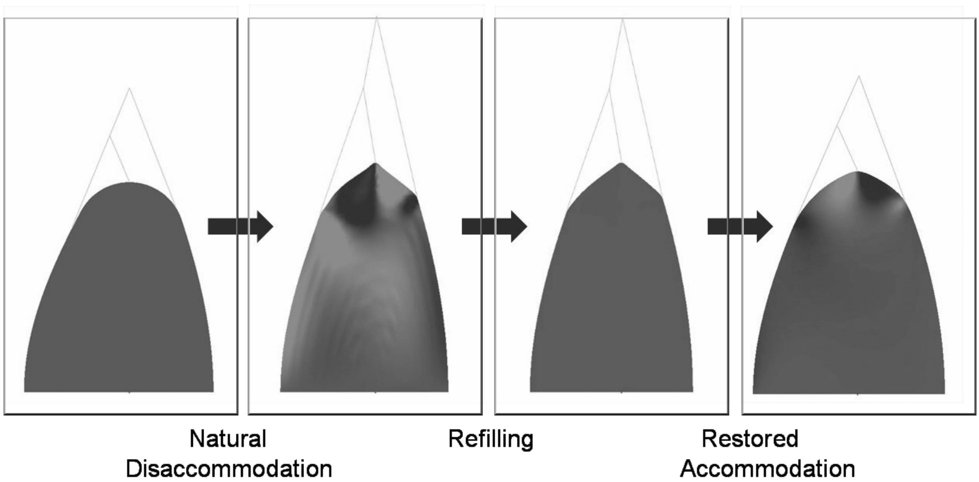

Figure 4. *Simulation of lens refilling. The grey shading depicts the shear stresses in the lens matrix. Presented at ESCRS 2006*[42].

8.4 Future Work

Over the last years, the mechanics of accommodation has gained a lot of interest in the scientific community. This concerns both measurements on eyes as well as mechanical modeling. Recent studies include new accurate measurements of the local thickness of lens capsules of different ages by Barraquer et al.[45] and Ziebarth et al.[46]. Using 3-dimensional ultrasound biomicroscopy, the structure of the zonular fibers has been imaged in vivo[47]. The mechanical behavior of the lens capsule is being carefully studied, describing its non-isotropic and non-linear behavior[48-50]. The mechanical characteristics of the crystalline lens are being further studied using fresh donor lenses[51,52], and a new in vivo technique for measuring mechanical properties of the lens seems promising[53].

New measurement data of the human eye can be used to improve mechanical models and with that the reliability and accuracy of the simulation outcomes. Finite elements modeling of the accommodative mechanism has been used frequently in the last few years[40,54-59]. As indicated earlier, proper validation of the model, related to relevant experiments, remains of crucial importance. Geometrical nonlinearity of the model has shown to be imperative for obtaining correct results[60]. It was also shown that models can describe the accommodative mechanism according to the principles of opposing theories of accommodation[55,61]. Keeping this in mind, mechanical models will be able to describe the accommodative process in ever more detail.

8.5 References

1. Dubbelman M, van der Heijde GL, Weeber HA. Change in shape of the aging human crystalline lens with accommodation. *Vision Res.* 2005;45:117-132.
2. Fisher RF. The elastic constants of the human lens. *Journal of Physiology.* 1971;212:147-180.
3. Dubbelman M, Van der Heijde GL, Weeber HA, Vrensen GF. Changes in the internal structure of the human crystalline lens with age and accommodation. *Vision Res.* 2003;43:2363-2375.

4. Weeber HA, Dubbelman M, van der Heijde GL. Verification of a mechanical model of accommodation versus real patient data *Invest Ophthalmol Vis Sci.* Fort Lauderdale; 2003.
5. Weeber HA. Mechanics of lens refilling. *European Association for Vision and Eye Research, Joint European Research Meeting in Ophthalmology and Vision.* 2003;35:150.
6. Koopmans SA, Terwee T, Barkhof J, Haitjema HJ, Kooijman AC. Polymer refilling of presbyopic human lenses in vitro restores the ability to undergo accommodative changes. *Invest Ophthalmol Vis Sci.* 2003;44:250-257.
7. Dubbelman M, Van der Heijde GL. The shape of the aging human lens: curvature, equivalent refractive index and the lens paradox. *Vision Res.* 2001;41:1867-1877.
8. Telandro AP, Steile Jr. Presbyopia: perspective on the reality of pseudoaccommodation with LASIK. *Ophthalmol Clin North Am.* 2006;19:45-69.
9. Dai GM. Optical surface optimization for the correction of presbyopia. *Appl. Opt.* 2006;45:4184-4195.
10. Menapace R, Findl O, Kriechbaum K, Leydolt-Koeppl C. Accommodating intraocular lenses: a critical review of present and future concepts. *Graefe's Arch Clin Exp Ophthalmol.* 2007;245:473-489.
11. Kessler J. Experiments in Refilling the Lens. *Arch Ophthalmol.* 1964;71:412-417.
12. Parel JM, Gelender H, Trefers WF, Norton EW. Phaco-Ersatz: cataract surgery designed to preserve accommodation. *Graefes Arch Clin Exp Ophthalmol.* 1986;224:165-173.
13. Haefliger E, Parel JM, Fantes F, Norton EW, Anderson DR, Forster RK, Hernandez E, Feuer WJ. Accommodation of an endocapsular silicone lens (Phaco-Ersatz) in the nonhuman primate. *Ophthalmology.* 1987;94:471-477.
14. Haefliger E, Parel JM. Accommodation of an endocapsular silicone lens (Phaco-Ersatz) in the aging rhesus monkey. *Journal of Refractive & Corneal Surgery.* 1994;10:550-555.
15. Nishi O. Refilling the lens of the rabbit eye after endocapsular cataract surgery. *Folia Ophthalmol (Japan).* 1987;38:1615-1618.
16. Nishi O, Nishi K, Mano C, Ichihara M, Honda T. Controlling the capsular shape in lens refilling. *Arch Ophthalmol.* 1997;115:507-510.
17. Koopmans SA, Terwee T, Glasser A, Wendt M, Vilipuru AS, van Kooten TG, Norrby S, Haitjema HJ, Kooijman AC. Accommodative lens refilling in rhesus monkeys. *Invest Ophthalmol Vis Sci.* 2006;47:2976-2984.
18. Treffers WF. Lens Replacement. In: Sears M, Tarkkanen A, eds. *Surgical Pharmacology of the Eye*. New York: Raven Press; 1985.p.237-249.
19. Cocteau MM, D'Etoille L. Reproduction du crystallin [Experiments relative to the reproduction of the lens]. *J Physiol Exp (Paris).* 1827;7:30-44.
20. Gwon A, Enomoto H, Horowitz J, Garner MH. Induction of de novo synthesis of crystalline lenses in aphakic rabbits. *Exp Eye Res.* 1989;49:913-926.
21. Gwon A. Lens regeneration in mammals: a review. *Surv Ophthalmol.* 2006;51:51-62.
22. van Alphen GWHM. Transplantation of the lens. *AMA Arch Ophth.* 1959;61:115-126.
23. Myers RI, Krueger RR. Novel approaches to correction of presbyopia with laser modification of the crystalline lens. *J Refract Surg.* 1998;14:136-139.

24. Blum M, Kunert K, Nolte S, Riehenmann S, Palme M, Peschel T, Dick M, Dick HB. [Presbyopia treatment using a femtosecond laser]. *Ophthalmologe.* 2006;103:1014-1019.
25. Gerten G, Ripken T, Breitenfeld P, Krueger RR, Kermani O, Lubatschowski H, Oberheide U. [In vitro and in vivo investigations on the treatment of presbyopia using femtosecond lasers]. *Ophthalmologe.* 2007;104:40-46.
26. Atchison DA. Accommodation and presbyopia. *Ophthalmic Physiol Opt.* 1995;15:255-272.
27. Adler-Grinberg D. Questioning our classical understanding of accommodation and presbyopia. *Am J Optom Physiol Opt.* 1986;63:571-580.
28. Fisher RF. The mechanics of accommodation in relation to presbyopia. *Eye.* 1988;2:646-649.
29. Gilmartin B. The aetiology of presbyopia: a summary of the role of lenticular and extralenticular structures. *Ophthalmic Physiol Opt.* 1995;15:431-437.
30. Glasser A, Campbell MC. Presbyopia and the optical changes in the human crystalline lens with age. *Vision Res.* 1998;38:209-229.
31. Weale RA. On the causes of presbyopia; letter. *Vision Res.* 1999;39:1263-1265.
32. Glasser A, Campbell MCW. On the potential causes of presbyopia; reply. *Vision Res.* 1999;39:1267-1272.
33. Glasser A, Campbell MCW. Biometric, optical and physical changes in the isolated human crystalline lens with age in relation to presbyopia. *Vision Research.* 1999;39:1991-2015.
34. Heys KR, Cram SL, Truscott RJ. Massive increase in the stiffness of the human lens nucleus with age: the basis for presbyopia? *Mol Vis.* 2004;10:956-963.
35. Koretz JF, Cook CA, Kaufman PL. Accommodation and presbyopia in the human eye. Changes in the anterior segment and crystalline lens with focus. *Invest-Ophthalmol-Vis-Sci.* 1997;38:569-578.
36. Pierscionek BK, Weale RA. Presbyopia - A maverick of human aging. *Arch Gerontol Geriatr.* 1995;20:229-240.
37. Strenk SA, Strenk LM, Koretz JF. The mechanism of presbyopia. *Prog Retin Eye Res.* 2005;24:379-393.
38. Coleman DJ, Fish SK. Presbyopia, accommodation, and the mature catenary. *Ophthalmology.* 2001;108:1544-1551.
39. Weale R. Presbyopia toward the end of the 20th century. *Surv Ophthalmol.* 1989;34:15-30.
40. Schachar RA, Abolmaali A, Le T. Insights into the age-related decline in the amplitude of accommodation of the human lens using a non-linear finite-element model. *Br J Ophthalmol.* 2006;90:1304-1309.
41. Glasser A. Restoration of accommodation. *Curr Opin Ophthalmol.* 2006;17:12-18.
42. Weeber HA. *Accommodation amplitude after refilling the human capsule with a soft material*. London: ESCRS; 2006.
43. Norrby S, Koopmans S, Terwee T. Artificial crystalline lens. *Ophthalmol Clin North Am.* 2006;19:143-146, vii.

44. Martin H, Terwee T, Guthoff R, Schmitz KP. Finite element investigations into polymer refilled lenses *Annual Meeting of the German Association of Biomedical Engineering (DGBMT)*. Nuernberg; 2005.
45. Barraquer RI, Michael R, Abreu R, Lamarca J, Tresserra F. Human Lens Capsule Thickness as a Function of Age and Location along the Sagittal Lens Perimeter. *Invest Ophthalmol Vis Sci*. 2006;47:2053-2060.
46. Ziebarth N, Manns F, Uhlhorn SR, Venkatraman AS, Parel JM. Noncontact optical measurement of lens capsule thickness in human, monkey and rabbit postmortem eyes. *Invest Ophthalmol Vis Sci.* 2005;46:1690-1697.
47. Stachs O, Martin H, Behrend D, Schmitz KP, Guthoff R. Three-dimensional ultrasound biomicroscopy, environmental and conventional scanning electron microscopy investigations of the human zonula ciliaris for numerical modelling of accommodation. *Graefes Arch Clin Exp Ophthalmol.* 2005:1-9.
48. Heistand MR. Biomechanics of the Lens Capsule *Department of Biomedical Engineering*. College Station: Texas A&M University; 2004.
49. David G. Mechanics of nonlinear biomembranes: Application to ophthalmology *Department of Biomedical Engineering*. College Station: Texas A&M University; 2005.
50. Pedrigi RM, David G, Dziezyc J, Humphrey JD. Regional mechanical propertires and stress analysis of the human anterior lens capsule. *Vision Res.* 2007;47:1781-1789.
51. Manns F, Parel JM, Denham D, Billotte C, Ziebarth N, Borja D, Fernandez V, Aly M, Arrieta E, Ho A, Holden B. Optomechanical Response of Human and Monkey Lenses in a Lens Stretcher. *Invest Ophthalmol Vis Sci.* 2007;48:3260-3268.
52. Ziebarth N, Wojcikiewicz EP, Manns F, Moy VT, Parel JM. Atomic force microscopy measurements of lens elasticity in monkey eyes. *Mol Vis.* 2007;13:504-510.
53. Erpelding TN, Hollman KW, O'Donnell M. Mapping age-related elasticity changes in porcine lenses using bubble-based acoustic radiation force. *Exp Eye Res.* 2007;84:332-341.
54. David G, Humphrey JD. Finite element model of stresses in the anterior lens capsule of the eye. *Comput Methods Biomed Engin.* 2007;10:237-243.
55. Liu Z, Wang B, Xu X, Wang C. A study for accommodating the human crystalline lens by finite element simulation. *Computerized Medical Imaging and Graphics.* 2006;30:371-376.
56. Martin H, Guthoff R, Terwee T, Schmitz KP. Comparison of the accommodation theories of Coleman and of Helmholtz by finite element simulations. *Vision Res.* 2005;45:2910-2915.
57. Hermans EA, Dubbelman M, van der Heijde GL, Heethaar RM. Estimating the external force on the human eye lens during accommodation by finite element modelling. *Vision Res.* 2006;46:3642-3650.
58. Reilly M, Szabo B, Ravi N. Finite element analysis of a single lens fibre *Invest Ophthalmol Vis Sci*. Fort Lauderdale (FL); 2006.
59. Abolmaali A, Schachar RA. Sensitivity study on human crystalline lens accommodation. *Comput Methods Biomed Engin.* 2007;85:77-90.
60. Burd HJ, Judge SJ, Flavell MJ. Mechanics of accommodation of the human eye. *Vision Research.* 1999;39:1591-1595.

61. Belaidi A, Pierscionek BK. Modeling internal stress distributions in the human lens: Can opponent theories exist? *J Vis*. 2007;7:1-12.